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GRAVITY ANOMALIES AND STRUCTURE OF THE WEST INDIES PART I

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BY MAURICE EWING AND J. LAMAR WORZEL

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ABSTRACT

Seismic-refraction results and gravity data have been used to deduce the crustal structure from the ocean basin north of the Puerto Rico trench to the Caribbean Sea. It is concluded that the Mohorovičić discontinuity (characterized by compressional-wave velocities of about 8 km/sec) lies at 9 km. below sea level under the ocean basin, 12 km under the Caribbean Sea, at about 16 km under the trench, and at slightly shallower depth under Puerto Rico. The large negative gravity anomaly is attributed to a great thickness of sediments in the trench rather than to a "sialic root" due to a down-buckle of the crust under the trench, as formerly thought.

Turbidity currents are assigned an important role in the accumulation of the sediments. It is suggested that a trench formed in an unspecified way quickly collects sediments, largely by turbidity currents. When granitized and uplifted the sediments form an island arc like the West Indies. Contamination of basaltic lavas by the sediments can account for andesitic lavas, and the accompanying water, rather than being juvenile, is derived from sea water. The trenches at or near the continental margins confine continental debris to the continental margins and collect oceanic debris. The basaltic crust and this debris are first formed into an island arc and later into a continental addition.

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INTRODUCTION

New seismic and coring evidence indicates the need for a reconsideration of the gravity minimum associated with the West Indian island arc. Ewing (1952) and Vening Meinesz (1954) have already written on some of the aspects of the new data.

The seismic data are far from complete, owing largely to the failure to receive a shipment of explosives. It is expected that additional observations will be made in the next year. The present preliminary paper is offered to make available in written form the verbal communication on which Vening Meinesz (1954) has based important parts of his paper.

ACKNOWLEDGMENTS

Mr. George Sutton generously made available in advance of publication most of the seismic results used here. Mr. Bruce Heezen gathered together all the sounding data, did the contouring, and very kindly made his chart available in advance of publishing the topography of the Puerto Rico trench.

We wish to acknowledge the contributions of sounding data and the earliest seismic work in the area by Dr. J. B. Hersey.

Most of the seismic work was done under Contract N6-onr-271 with the Office of Naval Research and NObsr 43355 with the Bureau of Ships, both of the U. S. Navy.

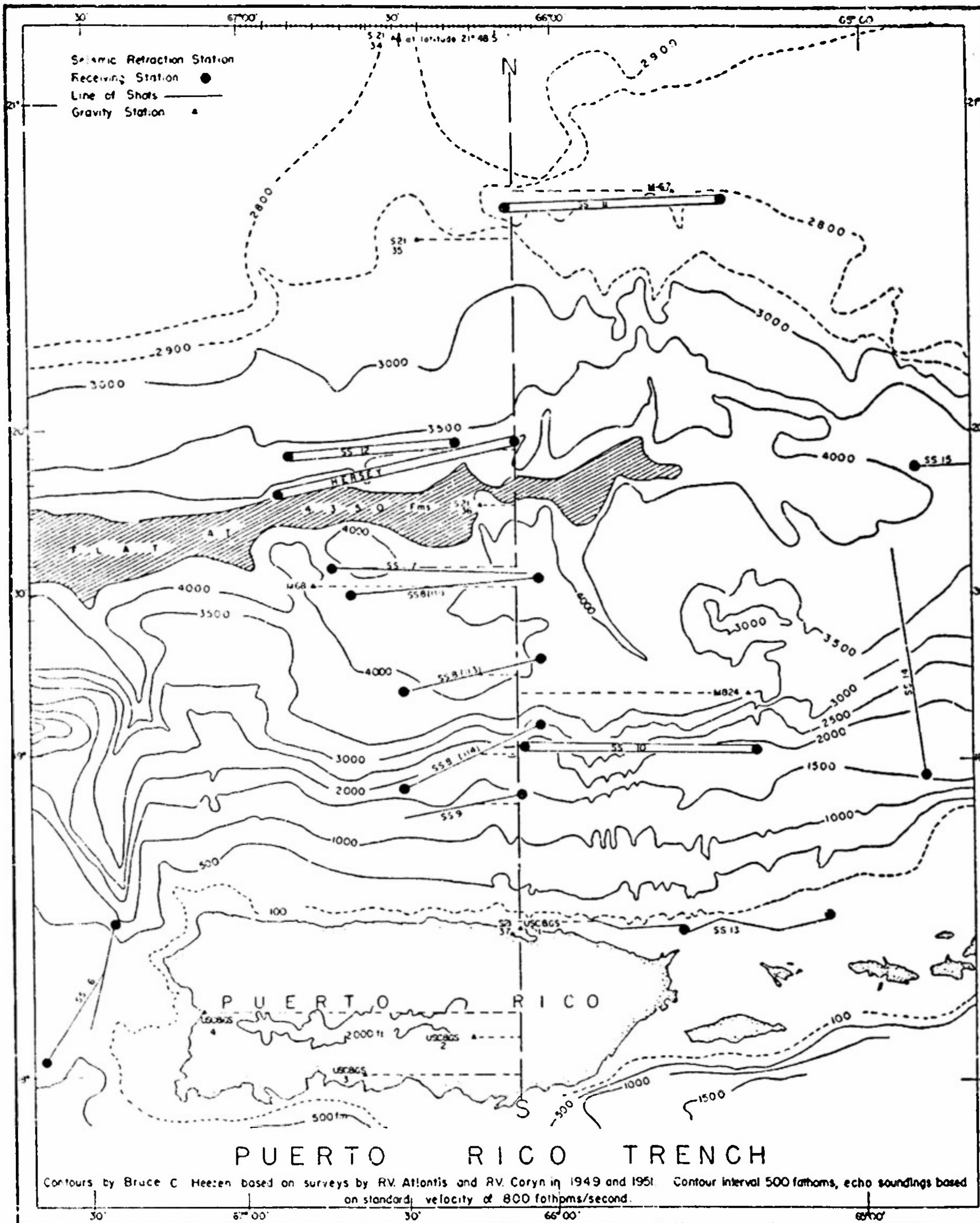

FIGURE 1.—CHART OF PUERTO RICO AREA

SEISMIC RESULTS

Six seismic-refraction measurements were made in the spring of 1951 in and near the trench north of Puerto Rico. These together with a measurement made by Hersey in 1949 are shown in Figure 1 superimposed on the best bathymetric chart available for publication, H.O. 5487. The locations of the gravity stations observed by Vening Meinesz and the U. S. Coast and Geodetic Survey are also shown. A

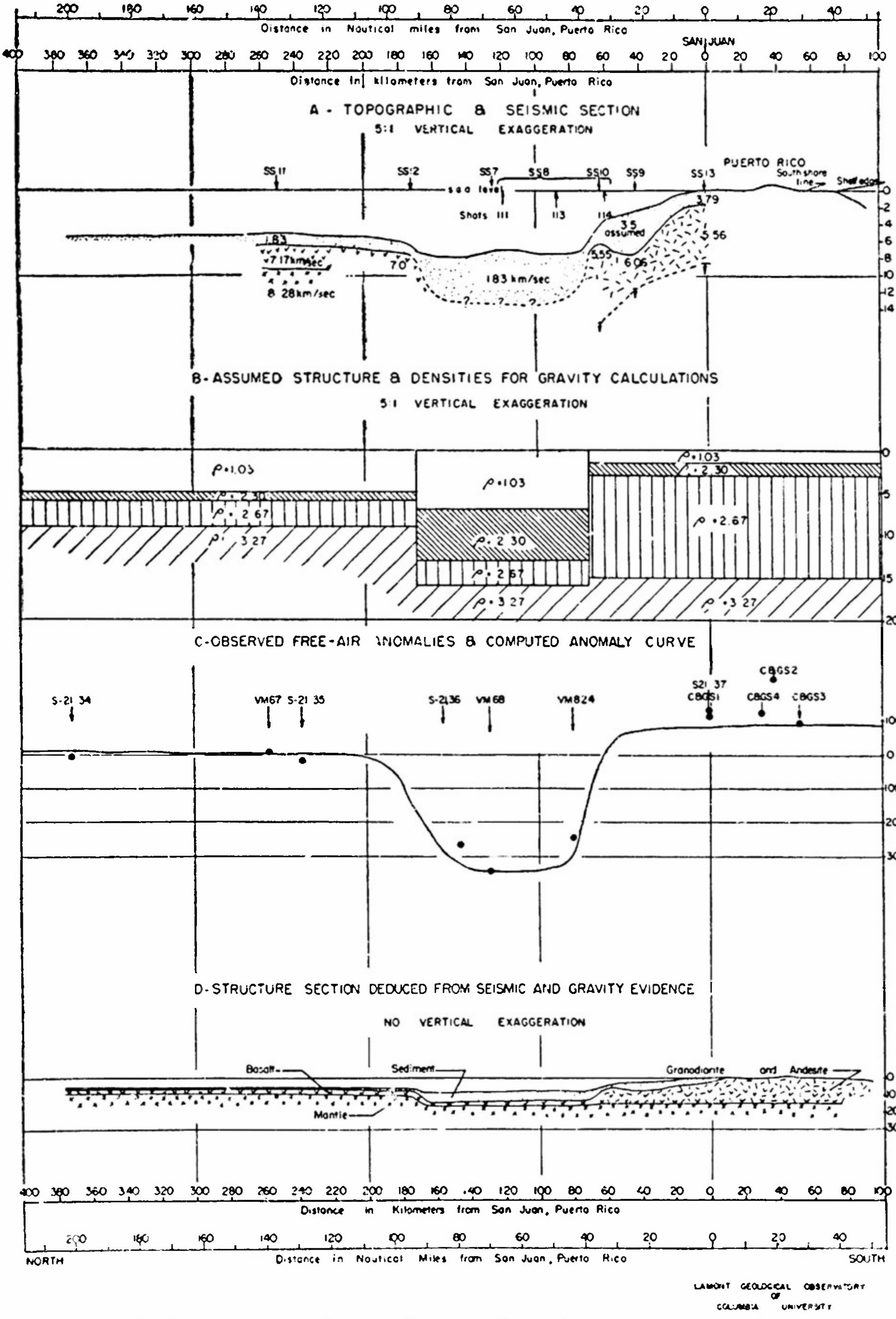

FIGURE 2.—STRUCTURE AND GRAVITY SECTIONS TRUE NORTH OF SAN JUAN, PUERTO RICO

north-south line of profile trending true north from San Juan, Puerto Rico has been chosen. The various data have been transferred to the line of section by moving them parallel to the strike of the topography. Figure 2A shows in section the topography and the observed seismic results. The observed sound velocities are indicated beneath each station.

S.S.-11 80 km north of the trench shows typical ocean-basin structure—*i.e.*, a 3 km-thick layer of 7.17 km/sec above the Mohorovičić discontinuity, overlain by a 1 km-thick layer of sediments in ocean depths of 5 km (Officer *et al.*, 1952, p. 801, 802; Ewing *et al.*, In press). S.S.-12 just north of the trench is similar, except the profile was not extended far enough to detect the Mohorovičić discontinuity. Hersey's results are, though fragmentary, essentially in agreement with S.S.-12. Similarly the results at S.S.-15 are in agreement, but they have not been included because of the large lateral displacement required to bring them into the line of section.

At stations S.S.-13, S.S.-9, and S.S.-10 south of the trench a layer of 5.5 to 6.0 km/sec was found under the sediments. The bottom of this layer has a *minimum* depth of 9 km, and the layer is quite comparable in velocity to the granitic layer under continents. The seismic data of S.S.-6 in Mona Passage have not been included here because of the obvious topographic difference from the line of section. The deeper layers in Mona Passage are in good agreement with S.S.-13. Seismic work in the Virgin Islands (Worzel and Ewing, 1948, p. 46) about 150 km to the east of the present section shows consolidated sediments (velocity 4.0 km/sec) of about .45 km thickness overlying a layer of 5.6 km/sec near the islands. The consolidated sedimentary layer thickens greatly toward the trench. This corresponds very well with the data near Puerto Rico.

Preliminary calculations on seismic-refraction measurements in the Caribbean indicate typical ocean-basin structure, as outlined above. Since the ocean-basin structure found north of the trench and in the Caribbean showed that the sialic layer was missing and the simatic layer was quite thin, making great difficulties for the accepted explanation of the gravity deficit in terms of a crustal down-buckle, it was expected that the trench would contain a great thickness of sediments.

At all the stations located within the trench —S.S.-7, S.S.-8 (shots 111 and 113), and S.S.-14 —the seismic measurements gave positive information only for the unconsolidated sediments; i.e. neither basement rocks nor consolidated or semi-consolidated sediments were detected. There is no question about the proper operation of the equipment since satisfactory results were obtained with it on days before, after, and in between the several observations in the trench. In more than 100 sea seismic stations, layers below the unconsolidated sediments have always been observed. On any interpretation of these results it must be concluded that the unconsolidated sediments are many kilometers thick.

Inability to map basement rocks beneath a thick sedimentary section by seismic-refraction measurements is not an uncommon experience on land or near the shore line. In such places, semi-consolidated or consolidated sediments were always found, and none were buried by more than about 1 km of unconsolidated sediment. In general at deep-sea refraction stations the entire sedimentary column (about 1 km) is apparently unconsolidated, although evidence on this point is inherently hard to obtain. It is remarkable that no velocities greater than those for unconsolidated sediments were observed in the trench. The compaction commonly found in a thick sedimentary column has not occurred here, perhaps because of very rapid accumulation of the sediment or because of the dependence of compaction on factors other than mere weight of overburden—*e.g.*, percolation of ground water.

One estimate of the minimum thickness of unconsolidated sediments can be made on the assumption that the explosive charge was sufficiently large to produce a readable signal, but the longer-shot distances were too short to permit reception of the basement-refracted wave. On this assumption the minimum sediment thickness is computed to be about 12 km. Another estimate can be based on the assumption that the great thickness of sediments causes sufficient absorption of energy to make the refracted wave too weak for observation. In effect this amounts to declaring that the longer shots of each profile must be excluded from the calculation of minimum depth. For many reasons it is impossible to make precise calculations of the absorption. A rough estimate may be made as follows: For comparable conditions at a typical deep-sea station the longest horizontal travel for the refracted wave travelling in unconsolidated sediments is 8–16 km. Assuming vertical and horizontal absorption are approximately equal, and that no other factors enter, the minimum thickness of sediments in the trench would be 4–8 km. Additional seismic-refraction measurements in the trench are needed.

Barbados, which lies on a continuation of the gravity minimum associated with the Puerto Rico trench, was investigated in 1944 (Worzel and Ewing, 1948, p. 48), and the basement rocks were not detected. It was concluded that about 1 km of unconsolidated sediments and 1 km of semiconsolidated sediments covered more than 3 km of consolidated sediments. This is consistent with the idea that the sediments were laid down under conditions now prevailing in the Puerto Rico trench.

Turbidity Currents

Ericson *et al.* (1951; 1952) and Heezen and Ewing (1952) have presented abundant evidence of the widespread operation, in the late Cenozoic oceans, of turbidity currents capable of carrying sediments hundreds of miles. The types of evidence of turbidity currents presented are sands containing shallow-water species of Foraminifera interbedded with oozes of abyssal facies, graded bedding in the turbidity-deposited layers with sharp lower boundaries, high-carbonate gray clays repeatedly alternating with red clays in basins, particles of shallow-water flora and fauna of Pleistocene and Recent age found in the turbidity-deposited layers at depths greater than 2000 fathoms, mineral and faunal similarity of deep-sea sands and continental-shelf sediments, and finally the flat floors of the deepest depressions being formed of numerous sedimentary layers exhibiting many alternations of colors and sediments.

The two cores (±10 feet long) taken in the flat plain on the bottom of the Puerto Rico trench clearly show deposition of much of the sediment by turbidity currents (Ericson *et al.*, 1952, p. 496–498, 509). These cores consist largely of thick graded calcareous sands containing shallow-water fauna and flora indicating a very large contribution of sediment to this trough from the surrounding shallow-water areas. Red clays are interbedded with the calcareous sands. Three cores on the north wall of the trench are normal deep-sea red clay throughout. Two cores on the south wall are essentially all clay, showing evidence of slumping. One is Pleistocene, the other Miocene. All of these cores are from depths so great that they would be expected to be red clay throughout if the deposition occurred in the absence of transportation along the bottom. Available bathymetric data indicate that a continuous ridge caps the north and east walls of the trench, cutting it off from turbidity currents from the main ocean basin. It is improbable that the barrier has been effective throughout the existence of the trench. Hence, if one grants the possibility of turbidity currents from the main ocean basin to the trench, it is reasonable to suppose that much of the sedimentary column contains a much smaller percentage of calcium carbonate than that reached by the coring tubes.

Gravity Results

Reconsideration of Vening Meinesz' (1934, p. 117–133; 1948, p. 25–90) and Hess's (1933; 1938, p. 71–86; 1951) hypothesis of the sialic crust down-buckling to form a local thickening of the sialic crust (tectogene) is required because of the seismic-refraction evidence that the sialic crust is absent under the Atlantic Ocean and under the Caribbean Sea. Vening Meinesz required a cross section of 1200 km^2 for a tectogene with a density contrast of 0.6 at the base of a 25- or 30-km crust, to produce the observed anomaly, corresponding to a crustal shortening of 50 or 40 km respectively. If the 3- to 5-km-thick layer found by seismic-refraction methods to overlie the Mohorovičić discontinuity and to underlie the sediments of the ocean floor was the source of the thickened section, the shortening required would be 250 to 500 km. The 1200 km^2 block calculated by Vening Meinesz was for the Java-Christmas Island profile where the largest isostatic anomaly was −130 mgals, whereas the largest isostatic anomaly reported by Vening Meinesz (1948, p. 230) for the trench north of Puerto Rico was −226 mgals (the largest negative anomaly reported to date). Thus more than 500 km of shortening would be required to produce the anomaly. Hess (1933, p. 31) prefers a crust with a density 0.3 less than the material beneath. This figure doubles the required crustal shortening.

The location of the gravity stations in the Puerto Rico area is shown in Figure 1. Vening Meinesz first discovered the negative gravity trough associated with this topographic trench on his world-circling cruise of Hr. Ms. K-XIII. On the cruise of the S-21 he made additional observations and again on Hr. Ms. 0 13. Heiskanen (1939, p. 98) has given the best values for the S-21 data, while Vening Meinesz (1948, p. 156, 230) has given the best values for the other cruises. Ewing (1937) has shown that the negative trough continues around the Windward Islands to Trinidad. None of the Barracuda measurements are considered in our section as all these values are too far to the east. The U. S. Coast and Geodetic Survey has made four gravity stations on Puerto Rico. Heiskanen (1939, p. 92) also lists these stations. The only isostatic anomaly computed for all the various stations is the Hayford isostatic anomaly with a depth of compensation of 113.7 km. Table 1 shows the various gravity stations, the water depth, the free-air anomalies, the Hayford isostatic anomalies, and the available Airy local isostatic anomalies for a crustal thickness of 30 km. Utilizing either the Hayford or the Airy theory, it is obvious that the trench is not in isostatic equilibrium. In fact the Airy hypothesis (T = 30 km) quickly leads to impossible situations. If one uses the local Airy hypotheses with T = 30 km, water density 1.03, crustal density 2.67, and subcrustal density 3.27, one finds that the subcrustal material lies at the ocean floor for water depths of 8 km and above the ocean floor for greater water depths. For T = 20 km this dilemma arises at water depths of 5.7 km, just slightly more than the mean ocean depth. If a density differential of 0.3 is chosen between the crustal density and the subcrustal density, these figures become 4.7 km for T = 30 km and 3.2 km for T = 20 km. Regional isostatic assumptions will not modify this picture appreciably.

Table 1.—Isostatic Anomalies in the Puerto Rico Area

Station		Water depth (Meters)	Free-air anomaly (Mgals)	Hayford isostatic anomaly (Mgals)	Airy local isostatic anomaly (T = 30 km)
S-21	34	5569	−18	−1	
	35	5340	+21	+31	
	36	7699	−264	−125	
	37	9	+129	−19	
Vening Meinesz	67	5510	+9	+7	+7
	68	8040	−341	−193	−292
	824	7370	−244	−226	−222
		Elevations			
U. S. Coast & Geodetic Survey	1	+8	+112	−43	On land
	2	+648	+220	+23	
	3	+14	+91	−48	
	4	+16	+122	−20	

Since isostatic assumptions of density distribution do not fit the data, we can discard the isostatic anomalies and go back to the free-air anomalies, trying other density distributions to account for the observed anomalies.

Structure Deducted from Seismic and Gravity Data

We have utilized the seismic evidence to form most of our picture, choosing a density of 2.30 for the sediments. We have chosen this density as about the best average for water-filled sediments (Birch *et al.*, 1942, p. 19–26). Although the sediments of the ocean bottom are subjected to great hydrostatic pressure, it is improbable that this causes compaction as a load of overburden does (Hedberg, 1936). While the thickness of overburden in the trench is sufficient to effect compaction, this sediment was probably collected so quickly that the compaction process has had insufficient time to operate, so that a density of 2.30 is probably a good figure.

We have made our computations for rectangular blocks extending to infinity in the directions parallel to the axis of the trench. This is quite as good a computation as the quantity of gravity data merits. We hope to obtain many gravity observations on a profile across the trench in the near future, and it would be more appropriate to use more sophisticated computations at that time.

The seismic data does not provide the necessary evidence for the thickness of the 5.5- to 6.0-km/sec layer near Puerto Rico, so we have adjusted this thickness until the gravity data matched fairly well. Likewise, we have neither measured the thickness of the sediments in the trough nor detected any underlying layers. We have assumed a crustal thickness like that found under the ocean north of the trench and have adjusted the sedimentary thickness until we obtained the best fit for the gravity data. Figure 2B shows the assumed structure and densities used in the computation of the best fit to the gravity data. Figure 2C shows the observed free-air anomalies plotted as points, and the results of our computation shown as a continuous curve. It is obvious that the fit is quite satisfactory.

It is interesting to note that a 6-km thickness of sediments is required to fit the gravity data for the trench and that the subsedimentary layer near Puerto Rico must be 12 km thick. If the sedimentary density were higher, the thickness of sediments would have to be greater. No unusual downbulge is required under the trough to explain the gravity anomalies.

Figure 2D shows without vertical exaggeration the structural section deduced from the seismic and gravity data. The existence of the basaltic (7.0–7.2 km/sec) layer under the trench and under Puerto Rico is purely hypothetical and is based on the notion that these were formerly normal oceanic crusts. The bulk of the material under Puerto Rico with a velocity of 5.5 to 6.0 km/sec is probably metamorphic rocks like those visible on the surface of Puerto Rico.

The negative gravity anomaly belt may be explained without demanding any significant crustal shortening or lengthening (Fig. 2D). Omitting the basaltic layer under the trench or doubling its thickness there would give a section that would not seriously contradict the seismic data. Owing to the slight thickness of the basaltic layer in undisturbed ocean-bottom crust, these limits of thickness would be consistent with crustal deformation ranging from 100 km of extension to an equally great shortening. In other words the solution offered in Figure 2 imposes no demands for large relative horizontal displacements of crustal segments. In fact it indicates that study of the gravity anomalies cannot be expected to give information about such displacements. The existence of strong belts of negative gravity anomalies near the southern and western borders of the Caribbean Sea (indicated by Vening Meinesz *et al.*, (1934), p. 156, 230 and Ewing (1937), but detailed in our recent unpublished measurements) make it very awkward to explain the large negative gravity anomalies along the northern and eastern boundaries by large horizontal crustal displacements.

Since seismic-refraction measurements permit only a very slight thickness of low-density crustal rocks either north or south of Puerto Rico, a thick prism of sediments seems to offer the only possibility of explaining the observed negative gravity anomalies.

We consider it of greatest importance to make additional seismic and gravity measurements in the West Indian area to obtain conclusions based entirely on positive and abundant data. It is obviously also important to obtain seismic-refraction measurements in the Pacific trenches —especially in the Marianas and the East Indies—to learn if the West Indian arc is typical.

Hypothesis on the Origin of the Island Arc and Some Consequences of It

The hypothesis is offered that the Puerto Rico trench with its rapidly accumulating sediments represents a first stage in the development of a landmass like the Greater Antilles. Without specifying the forces that cause the deep depressions to form or the sources of heat that elevate the temperature of magmas and lavas in general, we point out that granitization of a body of sediments like that now collecting in the Puerto Rico trench assuming that the bulk of the sediment is comparable to deep-sea sediments in general—*e.g.*, red clay, or like the oceanic formation on Barbados) would produce a mass of sialic rock that could be expected to rise and form an island arc when the force which caused the trench was relaxed. The Barbados rise and the Lesser Antillean arc would then represent intermediate stages.

Among the additional consequences of this hypothesis may be mentioned the following: (1) Andesitic lavas result from the contamination of basaltic-magmas, by the sediments during the granitization of the sediments. (2) Most of the water released by andesitic volcanoes is not juvenile water, but merely the sea water entrapped when the sediments were deposited.

Implications for Continental Growth

The formation of trenches at or near the edges of continents, the rapid filling of the trenches by sediments, the alteration of the sediments to sialic rocks, and the rise of these rocks to form island chains provide a means for confining continental debris to the proximity of continents despite the action of turbidity currents. Such trenches at present almost completely ring the Pacific Ocean, probably reducing the role of turbidity-current deposition in mid-ocean sedimentation far below that which it plays in the Atlantic. Types of present-day trenches range from extreme oceanic types such as the Marianas to extreme continental types such as the west coast of Central and South America. All these types have probably existed throughout much of geologic time and have probably bordered nearly every coast

The total depth of deep-sea sediment is somewhat less than 1 km. Only by impounding most of the continental debris near continental margins and by transfer of sediments from the ocean basins to the continental margins can such a small thickness be explained. The alternatives are either an average rate of sedimentation less than 1 mm per 500 years or a process of metamorphism of sediments at a depth of less than 1 km beneath the ocean floor.

A detailed consideration of the role of deep-sea sediment in continental growth will be deferred, but it is clear that the process we have described for the West Indian arc would greatly facilitate the growth of continents from an original crust of basaltic rocks as suggested by A. C. Lawson (1932), Marshall Kay (1951), J. Tuzo Wilson (1949), and others.

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GRAVITY ANOMALIES AND STRUCTURE OF THE WEST INDIES PART II

BY J. LAMAR WORZEL AND MAURICE EWING

From new seismic data and the gravity anomalies, the structure section north of Puerto Rico was deduced by Ewing and Worzel (1954, p. 166). The data were very sparse, and the structure section derived was therefore quite general. It was possible however to show that a large downward deflection of the crust into a tectogene did not occur, but that the large negative gravity anomaly was due to a small downward deflection of the crust (about 7 km) and a large accumulation of sediments. It was suggested that this is the first stage in the formation of an island arc.

According to this suggestion an island such as Puerto Rico was formed as follows: a trench formed, filled rapidly with sediments swept from ocean areas and from near-by island arcs or land largely through the action of turbidity currents, the sediments were granitized, and the basaltic layer beneath the trench was contaminated producing andesitic lavas (the water accompanying the andesitic volcanic activity being derived from sea water associated with the sediments). This process implies that trenches, which habitually form in oceanic crust near the edges of continents, upon relaxation or reversal of the force responsible for the trench, collect most of the continental and oceanic debris forming an island arc. The area between island arc and continent is eventually added to the continent.

In the spring of 1953 measurements on board USS DIABLO (SS479) added 44 new gravity stations to a profile extending from about 200 miles due north to 200 miles due south of San Juan, Puerto Rico. Figure 1 shows the location of these stations as well as the locations of the gravity stations and seismic stations used in the earlier work. The Columbia University Frost type geodetic gravimeter was taken along, and one observer was put ashore on Puerto Rico to make additional land measurements. Four hundred new gravity stations were made in a network covering the whole island of Puerto Rico. These data are soon to be reported by Mr. Lynn Shurbet.

Figure 2A shows the known seismic and topographic data along the line of profile. Figure 2B shows the layers and densities from which a computed gravity curve was obtained. Figure 2C shows the gravity data and the computed curves. The solid dots are the gravity data used in Part I. The open circles show the free-air anomalies at the new gravity-at-sea stations. The dotted curve over the island of Puerto Rico shows the modified Bouguer anomalies along the line of profile. The double dash-and-dot curve over the island of Puerto Rico shows the average modified Bouguer anomalies of five profiles across the island of Puerto Rico made available by Mr. Shurbet prior to publication. The solid line is the anomaly curve computed from the mass distribution used in Part I. The dashed curve shows the anomaly curve computed for the mass distribution shown in Figure 2B, on the assumption that measurements are made at sea level. This computed anomaly curve quite satisfactorily fits the free-air anomalies for sea stations and the modified Bouguer anomalies for land stations. The oscillations in the computed curve would be smoothed out if the computations were made for the blocks having inclined boundaries instead of the rectangular forms used here. In this form the computations would have been more laborious and would have added little to the picture.

Figure 2D shows the section derived from the seismic and the gravity data without vertical exaggeration. The section to the north of San Juan is changed from our previous work by the addition of more detail, which is now justified by the additional data. South of Puerto Rico the new gravity minimum of almost −160 milligals is accounted for by a slight downward deflection of the crust and a thick column of sediments. Because of lack of time, the gravity observations at sea could not be continued in close to the south shore of Puerto Rico.

This more detailed and extended profile confirms all of the interpretations and conclusions made in our previous report and requires no modifications of the hypothesis and the implications introduced there.

Thanks are due Mr. Lynn Shurbet and Mr. Hugh Traphagen who made all the new gravity observations. Mrs. Elizabeth S. Skinner did most of the calculations for the gravity-at-sea data, and Mr. Lynn Shurbet did all the calculations of the land gravity measurements. Miss Annette Trefzer did the drafting.

To the officers and men of USS DIABLO we wish to express our appreciation for their interest and assistance in making the gravity observations at sea.

Professor Raoul C. Mitchell and Don Luis Stefani of the University of Puerto Rico provided much valuable advice and assistance in the course of the measurements on Puerto Rico.

Transportation was generously provided by Dr. R. Fernandez Garcia, Director, Industrial Research Department, Economic Development Administration of the Commonwealth of Puerto Rico.

Dr. Raymond J. Smith of the United States Geological Survey provided much assistance.

Most of this work was carried out under contract N6 onr 271 with the office of Naval Research of the Department of the Navy. Financial assistance for the land gravity work was made available by the University of Puerto Rico.

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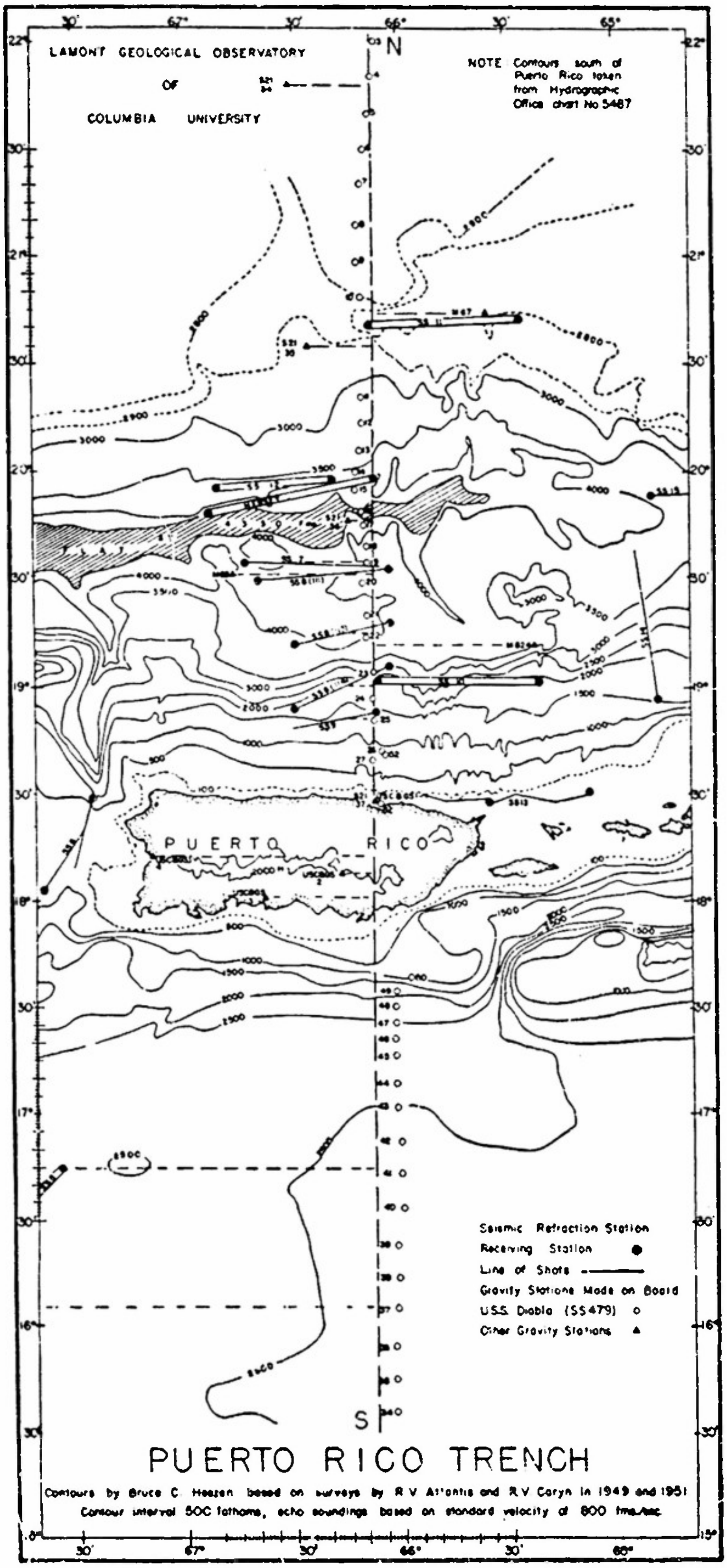
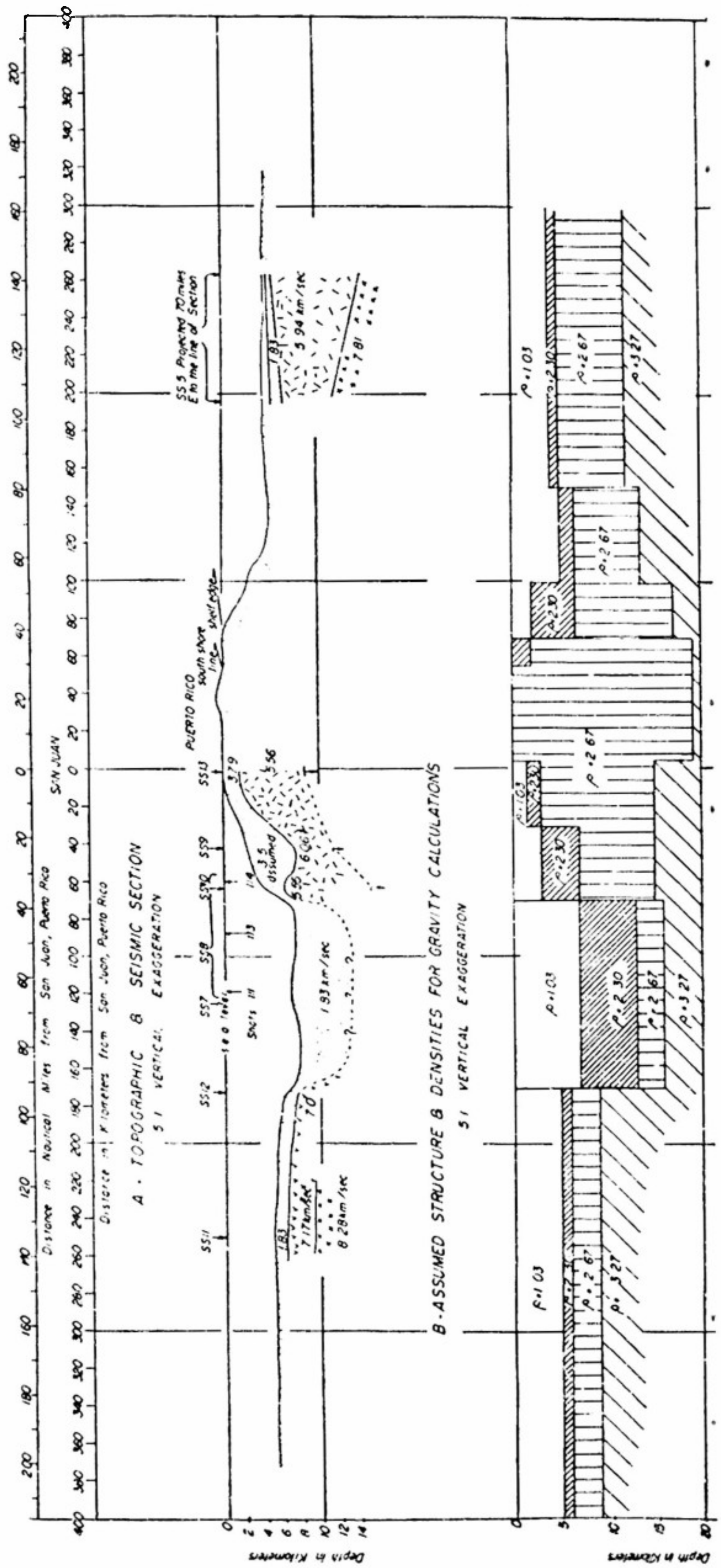


FIGURE 1.—PUERTO RICO TRENCH


A. TOPOGRAPHIC & SEISMIC SECTION
5:1 VERTICAL EXAGGERATION
Distance in Nautical Miles from San Juan, Puerto Rico
Distance in Kilometers from San Juan, Puerto Rico
SAN JUAN
PUERTO RICO
B. ASSUMED STRUCTURE & DENSITIES FOR GRAVITY CALCULATIONS
5:1 VERTICAL EXAGGERATION
Depth in Kilometers
Depth in Kilometers

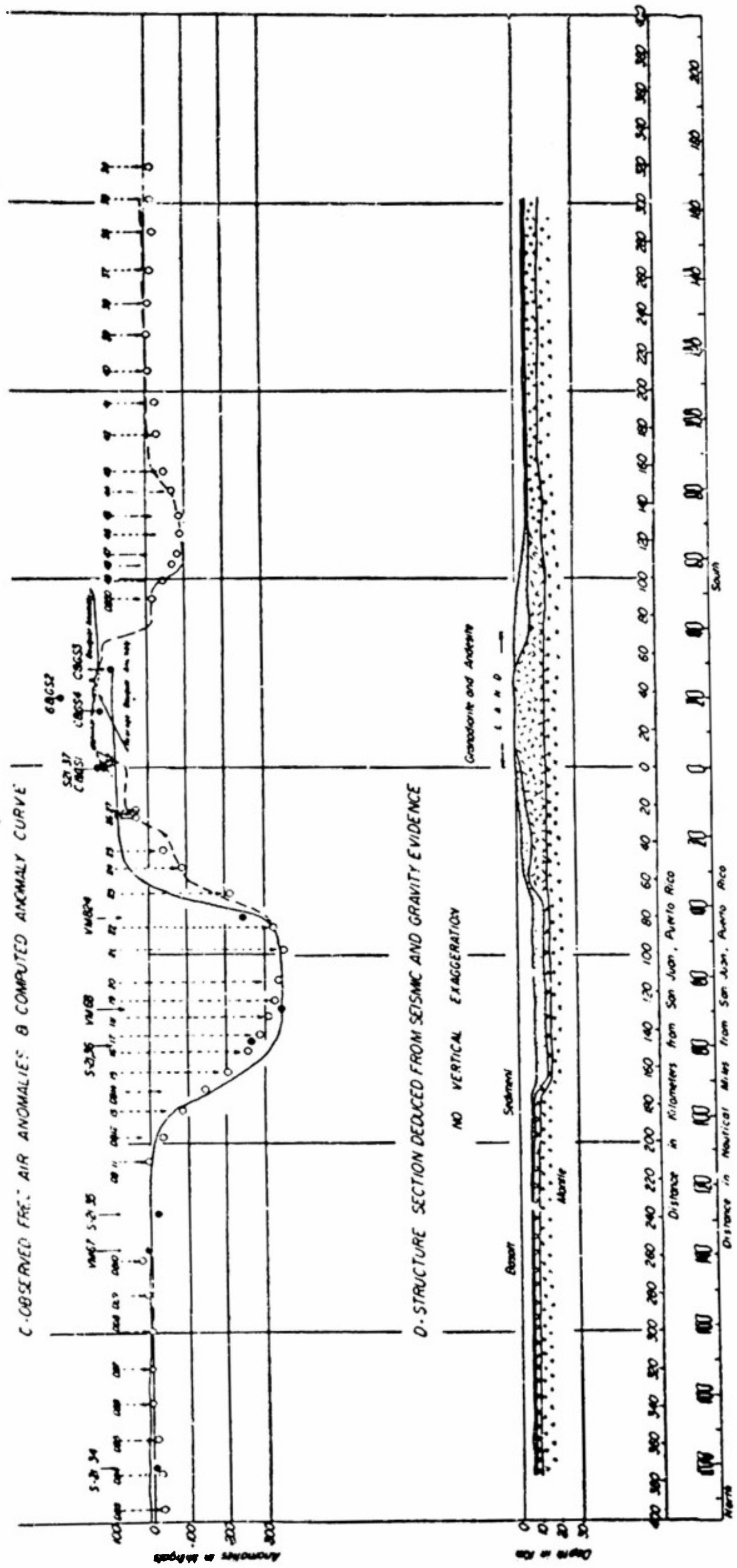


FIGURE 2.—NORTH-SOUTH STRUCTURE AND GRAVITY SECTIONS THROUGH SAN JUAN, PUERTO RICO